Event shapes and other QCD studies at LEP

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Abstract

QCD results on jet rates, event shapes and inclusive charged particle spectra in hadronic events from e^-e^+ annihilations at LEP up to a center-of-mass energy of 208 GeV are presented.

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1. Introduction

With the increase of center-of-mass energy ($\sqrt{s}$), LEP provides an ideal environment for precise tests of QCD over a wide energy range with small hadronization corrections, which scale inversely as $\sqrt{s}$. In this paper, results up to $\sqrt{s} = 208$ GeV from the LEP experiments: ALEPH [1], DELPHI [2], L3 [4,5] and OPAL [6,7] are reviewed. Radiative Z-decay events with isolated photons, provide information on the hadronic system down to $\sqrt{s} = 30$ GeV [2,4]. From quark and gluon jet multiplicities measured at the Z peak, colour factors are obtained [3].

2. Jet Rates

Hadronic events are characterised by a multi-jet topology. Jets have been studied using the Jade, Durham and Cambridge algorithms. Figure 1 shows the different jet rates for year 2000 data using the Cambridge algorithm [5]. Satisfactory agreement with the predictions of QCD models is obtained.

NLO predictions for 4 jet rates are now available [8]. α_s measured by DELPHI [2] using Cambridge algorithm ($y_{cut} = 0.004$) are compared to $\mathcal{O}({\alpha_s}^3)$ calculations in figure 2. Fit to $\frac{d{\alpha_s}^{-1}}{d \log E_{cm}}$ gives 1.17 ± 0.28, in agreement with expectation of 1.27 for 5 flavours.

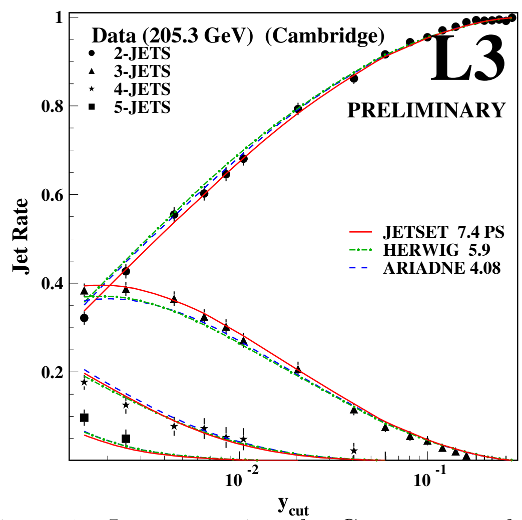

Figure 1. Jet rates using the Cambridge algorithm.

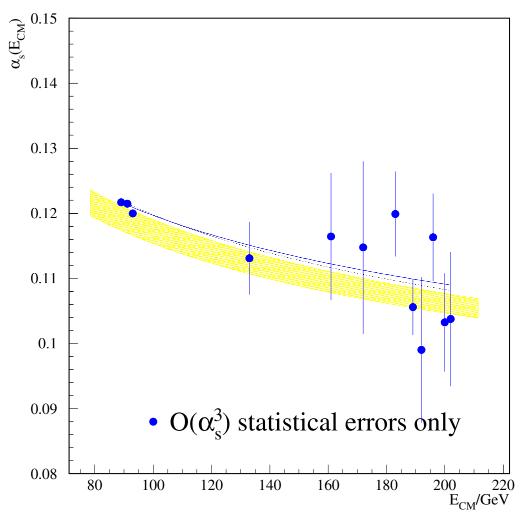

Figure 2. α_s from 4 jet rates.

3. Event Shapes

The energy flow in hadronic events can be conveniently studied in terms of collinear and infrared safe global event shape variables. The energy dependence comes from logarithmic behaviour in α_s, as well as inverse power dependence from non-perturbative effects.

For some event shape variables, like thrust (T), heavy jet mass (ρ), total and wide jet broadenings (B_T and B_W) and the C-parameter (C), complete theoretical calculations exist up to $\mathcal{O}({\alpha_s}^2)$ and the leading and next-to-leading order terms have been resummed up to all orders. While the second order calculations work well in the multi-jet region, the resummed calculations are necessary to describe the data in the two jet region. Thus the whole distribution of the event shapes can be used, giving reduced statistical errors in the determination of α_s.

4. Determination of α_s

4.1. Power Law ansatz

Assuming the soft gluon emission is controlled by an effective coupling ($\alpha_{\rm eff}$), which differs from α_s in the infrared region, the hadronization correction to the non-perturbative component of moments as well as the differential distributions of event shapes can be parameterised using a power law ansatz. The mean values and the distributions have been simultaneously fitted to $\alpha_s(M_Z)$ and the non-perturbative parameter $\alpha_0(\mu_I)(= \frac{1}{\mu_I}\int_0^{\mu_I} dq\alpha_{\rm eff}(q))$ at a scale $\mu_I = 2$ GeV, using second order calculations for the perturbative part. The results of α_s and α_0 from fits to moments and distributions are shown in the figure 3. The scatter in the measurements from different variables between the different experiments being large, universality of α_0 is verified within $\pm$ 20%.

Phenomenological study [2] shows that the relative size of the power law contribution is large for event shapes variables with large relative second order term. L3 studied [4] the second moment of the event shapes using an additional 1/s term in the power law parametrization. The contribution is small for ρ, negative for B_W and substantial for others.

4.2. Resummed LL & NLL + $\mathcal{O}$ (${\alpha_s}^2$)

The standard determination of α_s from event shape variables uses matching of second order predictions with resummed NLLA calculation. Quark mass effects are included in the $\mathcal{O}$ (${\alpha_s}^2$) calculations: while the effect is 1% at M_Z, it scales as 1/s down to 0.2% at 200 GeV. Fits to the five event shape variables measured by L3 [5] at $\sqrt{s}$ = 206 GeV are shown in the figure 4.

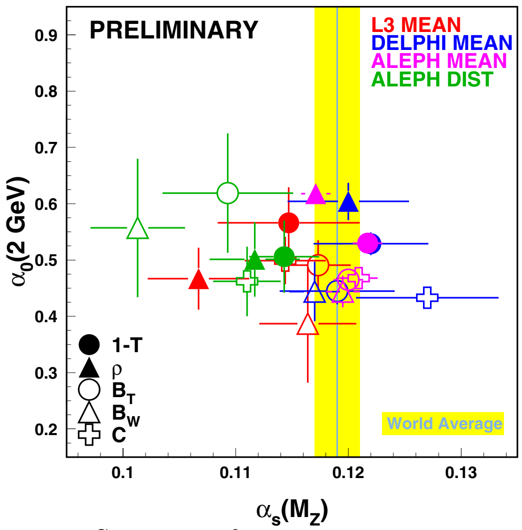

Figure 3. Summary of α_s-α_0 measurements.

The measurements of α_s using the different event shapes are averaged for each value of $\sqrt{s}$, and evolved to M_Z for comparison in the figure 5. The average of all the measurements gives:

$$\alpha_s(M_Z) = 0.1204 \pm 0.0007(\text{exp}) \pm .0034(\text{theo})$$

From a fit to the slope of the α_s measured between 30 and 208 GeV by the L3 [5], the number of active quark flavours is obtained to be 5.1 $\pm$ 1.3 (exp) $\pm$ 1.9 (theo), in agreement with DELPHI measurements [2] of $\frac{d{\alpha_s}^{-1}}{d\log E_{cm}}$.

5. Charged Particle spectra

Beyond the leading logarithmic approximation, the *intrajet coherence* phenomena arising from destructive interference between the soft gluon emission within the jets, reduces the phase space available for further parton emission to an angular ordered region. This dynamical suppression of the soft momenta leads to energy and emission angle ordering of successive parton radiations. It results in reduced parton multiplicities and a dip in the parton momenta in the low momentum region.

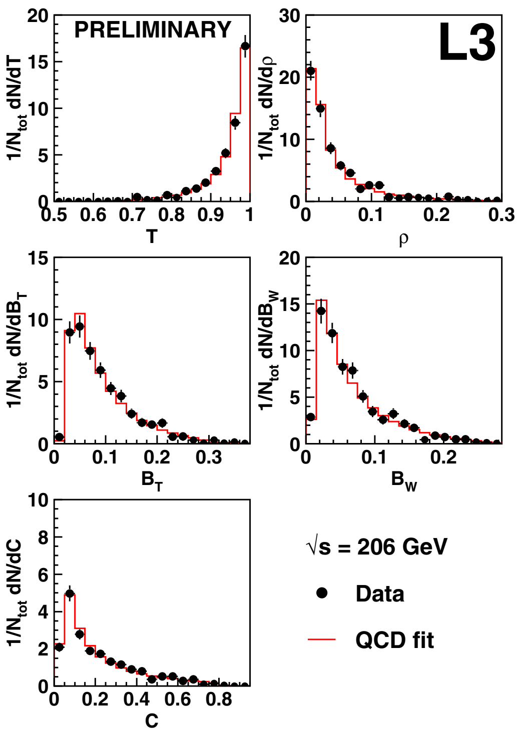

Figure 4. $\mathcal{O}$ $(\alpha_s{}^2)$ + resummed calculations fit.

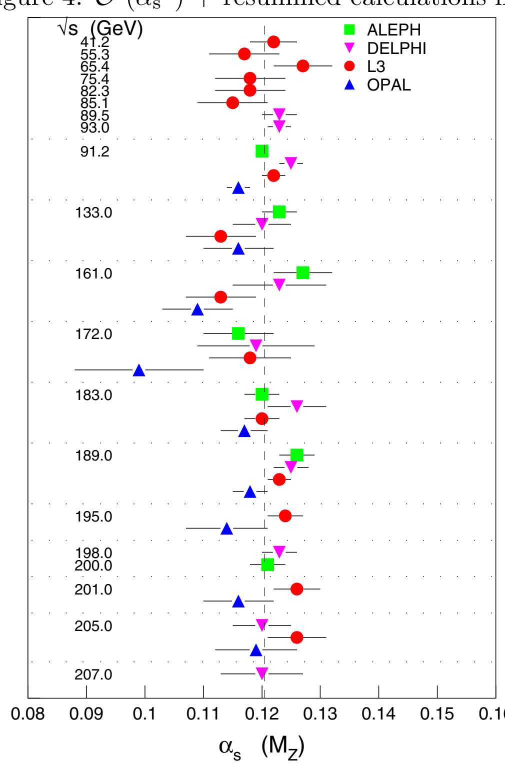

Figure 5. α_s measurements from event shapes.

The *charged particle momentum spectrum* is studied in terms of the variable $\xi = -\ln(\frac{2|\vec{p}|}{\sqrt{s}})$ (where $\vec{p}$ is the momentum). The energy evolution of the charged particle multiplicity and the measured peak position $(\xi^\star)$ (figures 6, 7) provide evidence for gluon coherence: predictions without coherence effects fail to describe the data.

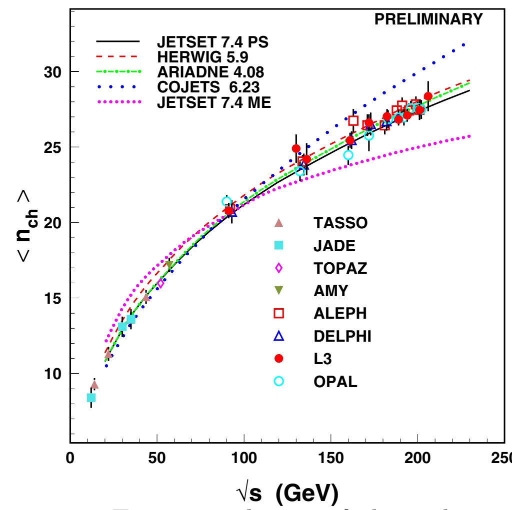

Figure 6. Energy evolution of charged particle multiplicity.

6. Quark and gluon multiplicities

The evolution of the charged particle multiplicity has been studied as a function of the opening angle (θ) between the sub-leading jets in mirror symmetric 3 jet events [3]. Correcting for the case when the gluon fragments into the leading jet, large opening angles translate into harder gluon jets, giving higher multiplicities.

Recent theoretical calculations relate the derivatives of quark-gluon multiplicities to the QCD colour factors [9]. From a fit to the data from hadronic Z decays, DELPHI updated their analysis using the CAMBRIDGE jet algorithm, and obtained: $\mathrm{C_A/C_F} = 2.221 \pm 0.047$ (exp) $\pm$ 0.058 (had) $\pm$ 0.075 (theo), in good agreement with the QCD prediction of 9/4.

The gluon-gluon multiplicity is extracted at scales given by $\sqrt{s}$ and $\mathrm{p_T}$ using the relation:

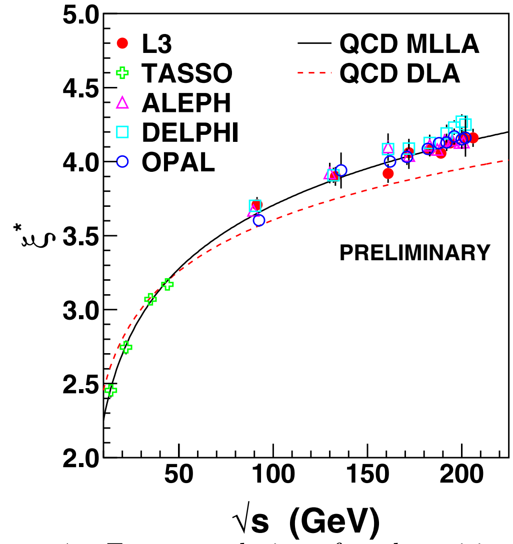

Figure 7. Energy evolution of peak position of ξ-spectra.

$N_{gg} = 2[N_{q\bar{q}g}(\theta) - N_{q\bar{q}} - N_0]$, estimating the non-perturbative offset term (N_0) from CLEO data. Measurements of the quark and gluon jet multiplicities are shown in the figure 8.

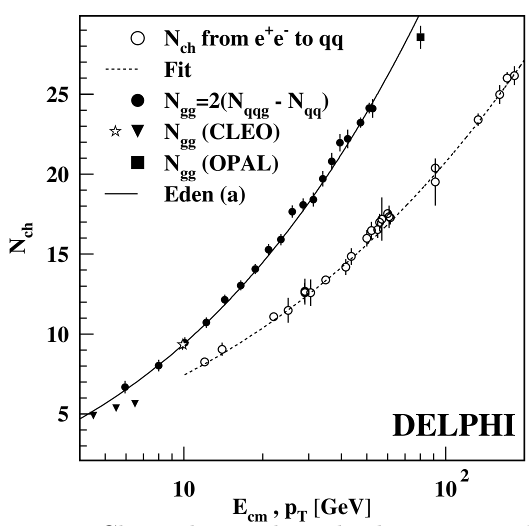

Figure 8. Charged particle multiplicity in quarks and gluon jets.

Summary

Different aspects of hard and soft gluon radiation have been studied in hadronic events with $\sqrt{s}$ in the range 30 to 208 GeV. Evidence of gluon coherence and higher gluon colour charge have been observed. The strong coupling constant, the number of active quark flavours and QCD colour factors have been measured.

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